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Fusion of strings and cosmic rays at ultrahigh energies

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Abstract

It is shown that the fusion of strings is a source of particle production in nucleus–nucleus collisions outside the kinematical limits of nucleon–nucleon collisions. This fact, together with another effect of string fusion, the reduction of multiplicities, sheds some light on two of the main problems of ultrahigh energy cosmic rays, the chemical composition and the energy of the most energetic detected cosmic rays.

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In the standard models of hadronic interactions ([1, 2, 3, 4]), strings, chains or pomerons are exchanged between the projectile and target. The number of strings grows with the energy and with the number of nucleons of the participant nuclei. In the first approximation strings fragment into particles and resonances in an independent way. However, the interaction between strings becomes important with their number growing. This interaction has been introduced into some of the models ([5, 6, 7, 8, 9, 10]). In particular, fusion of strings has been incorporated into the Dual Parton Model (DPM) ([8]) and the Quark Gluon String Model (QGSM) ([11]). Some of the effects of string fusion like strangeness and antibaryon enhancement ([12]), reduction of long range correlations ([13]) and multiplicity suppression have been studied comparing the results with the existing experimental data. Also predictions for the Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) are avalaible. In this paper we explore another effect of string fusion, namely particle production in nucleus–nucleus collisions outside the kinematical limits of nucleon–nucleon collisions (the so–called cumulative effect).

It is shown that this effect is important already at present avalaible energies. A non negligible number of baryons and mesons are produced with momenta greater than the ones of the colliding nucleons. This effect, together with the reduction of multiplicities, provides a natural explanation of some features of cosmic ray data like the rise of the average shower depth of maximum X_{max} (the amount of air penetrated by the cascade when it reaches maximum size) ([14, 15]) with increasing energy from 10^{17} eV to 10^{19} eV, and the existence of events with energy above 10^{20} eV ([14, 16, 17]), higher than the expected cut–off ([18, 19, 20]) due to the scattering of cosmic rays with the microwave radiation background. Usually the first feature is explained by an enrichment of protons in the composition of primary cosmic rays ([15]) as energy increases. However, as we show, if the composition of the primary cosmic rays is kept fixed in the energy range between 10^{17} eV and 10^{19} eV, string fusion leads to a suppression of the multiplicity similar to the one produced by changing heavy nuclei (Fe) by protons in the composition of the primary. On the other hand, since the momentum of a fused string comes from summing the momenta of its ancestor strings, it is possible to obtain particles with more energy than the initial nucleon–nucleon energy. Therefore, if several strings fuse, the observed cosmic ray events with energy above 10^{20} eV may actually correspond to three or four times less initial energy than that apparently measured. String fusion could make these events compatible with the existence of above mentioned cut–off.

To study these effects we use a Monte Carlo code based on the QGSM, in which the fusion of strings has been incorporated ([11]). A detailed description of the Monte Carlo String Fusion Model (SFMC) and comparison with experimental data can be found in Ref. [11, 12, 13]. A hadron or nucleus collision is assumed to be an interaction between clouds of partons formed long before the collision. Without string fusion partons are assumed to interact only once. Each parton–parton interaction leads to the creation of colour strings. Since both the projectile and the target must remain colourless, strings have to be formed in pairs. Hadrons and nuclei are considered on the same footing. The nuclear wave function is taken as a convolution of the parton distribution in a nucleon with the distribution of nucleons in the nucleus (given by the Wood–Saxon shape).

Strings fuse when their transverse positions come within a certain interaction area, which is fixed previously to describe correctly the strangeness enhancement ([12]) shown by the data on nucleus–nucleus collisions. The fusion can take place only when the rapidity intervals of the strings overlap. It is formally described by allowing partons to interact several times, the number of interactions being the same for projectile and target. The quantum numbers of the fused string are determined by those of the interacting partons and its energy–momentum is the sum of the energy–momentum of the ancestor strings. The colour charges of the fusing string ends sum into the colour charge of the resulting string ends according to the $SU(3)$ composition laws. In particular, two triplet strings fuse into an antitriplet and a sextet string, with probabilities 1/3 and 2/3 respectively. A triplet and an antitriplet string give rise to a singlet state and an octet string with probabilities 1/9 and 8/9 respectively. In present calculations only fusion of two strings is taken into account.

Particle production outside the nucleon–nucleon kinematical limits is a well known effect called cumulative effect, studied both theoretically and experimentally ([22, 23, 24, 25, 26]). However at high enough energies, where the string picture can be applied, there are only data from one collaboration at 400 GeV/c ([26]), with incoming protons against nuclei: Li, Be, C, Al, Cu and Ta. Generating p–A events in our code and comparing the cumulative particle spectrum with these data we observe a reasonable agreement, as can be seen in Tables 1 and 2 where the invariant differential cross sections for production of protons, positive pions and positive kaons are shown.

Passing to nucleus–nucleus collisions, 10000 central S–S collisions and 1000 central Pb–Pb collisions were simulated at $\sqrt{s} = 19.4$ AGeV. Also central Pb–Pb collisions at

RHIC energies ($\sqrt{s} = 200$ AGeV) have been simulated. Distributions of baryons and mesons in central S–S and Pb–Pb collisions at SPS energies with x_F larger than 1 are shown in Fig. 1 and 2. The results for Pb–Pb collisions at $\sqrt{s} = 200$ AGeV are very similar to the ones at $\sqrt{s} = 19.4$ AGeV. In 1000 events 2015 particles are found with $|x_F|$ larger than 1 to compare with 1783 at $\sqrt{s} = 19.4$ AGeV. This small change is due to a moderate increase of the number of strings with energy.

To study the case relevant for cosmic rays we simulated 1000 Fe–Air collisions at 10^{17} eV (we used this energy and not 10^{20} eV to save computing time, rendering the simulation reliable). In this sample 198 particles with $|x_F| > 1$ were found. The average number of strings was found to be 225, from which 62 joined to form double strings. As mentioned, our code only includes fusion of two strings. However we can estimate the number of strings participating in a triple fusion assuming that the probability for triple fusion is roughly the square of that for double fusion. Then one would expect that 18 strings join to form triple strings and 4 strings join to form a quadruple string. Therefore the probability of obtaining particles with $|x_F| > 2$ or even $|x_F| > 3$ does not seem to be negligible. The energy around $3 \cdot 10^{20}$ eV measured in several cosmic ray experiments could then be lowered by a factor 2 to 4 if the described effect is present and there are particles in the shower with $|x_F| > 2$ or $|x_F| > 3$. This lower energy for the primary may lie below the energy cut–off due to the scattering of cosmic rays on the microwave background.

On the other hand, string fusion produces a suppression of multiplicities, which can explain the rise of the average shower depth of maximum in cosmic rays as the energy increases, without requiring any change in the chemical composition. It is usually accepted that there is a change in the cosmic ray chemical composition between 10^{16} eV and 10^{19} eV. It seems that the composition becomes significantly lighter with increasing energy, going from a heavy composition at 10^{16} eV to a light one at energies higher than 10^{19} eV. According to this, the distribution of the shower depth of maximum as a function of energy has been studied using a simple model of two components ([15]), observing that the change in the composition of the primary goes from approximatly 75 % of iron component and a 25 % of proton component at 10^{16} eV to 50 % of iron and a 50 % of proton at 10^{19} eV. To study this point, we have computed the multiplicities of p–Air and Fe–Air interactions with and without string fusion in the whole range of energies studied (from 10^{16} to 10^{19} eV). As it can be seen in Fig. 3, with string fusion the multiplicity for a constant composition of 10 % of proton and 90 % of iron in the

whole range of energy, essentially reproduces the multiplicity obtained without string fusion for a uniform change in the composition from 75 % Fe and 25 % proton at 10^{16} eV to 50 % Fe and 50 % proton at 10^{19} eV. Thus the string fusion does the same job as the composition change.

Therefore, the change in the energy behaviour of the average shower depth of maximum X_{max} can be due to a change in the interaction mechanism with the existence of collective effects like string fusion, and not to a change in the chemical composition of the primary cosmic rays. Further studies of this point would require combining the code used in this paper with the standard codes which describe the full cascade. Work in this direction is in progress.

Summarizing, string fusion in nucleus–nucleus collisions produces a considerable number of particles outside the kinematical limits. This effect, together with the predicted suppression of multiplicities may help to understand the high energy cosmic rays including the chemical composition of primaries and the bound on the highest cosmic ray energy. Predictions of string fusion can be detected in future experiments at RHIC, LHC and cosmic ray experiments (concretely the Auger proyect ([27])).

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Table captions

Table 1. Comparison of experimental data ([26]) on the invariant differential cross section $\sigma = E\frac{d\sigma}{dp_3}$ for π^+ and K^+ vs p (GeV/c), laboratory angle 118^o, $P_{lab} = 400$ GeV, for p–Li and p–Ta collisions with the String Fusion Model code results, with and without string fusion.

Table 2. Comparison of experimental data ([26]) on the invariant differential cross section $\sigma = E\frac{d\sigma}{dp_3}$ for protons vs p (GeV/c), laboratory angle 118^o, $P_{lab} = 400$ GeV, for p–Li and p–Ta collisions with the String Fusion Model code results, with and without string fusion.

Figure captions

Fig. 1. x_F distributions for $x_F > 1$ in S–S collisions (10000 events) at $\sqrt{s} = 19.4$ AGeV of mesons (a) and baryons (b) with (continuous line) and without (dashed line) string fusion. No mesons are found in the no fusion case.

Fig. 2. x_F distributions for $x_F > 1$ in Pb–Pb collisions (1000 events) at $\sqrt{s} = 19.4$ AGeV of mesons (a) and baryons (b) with (continuous line) and without (dashed line) string fusion. No mesons are found in the no fusion case.

Fig. 3. Total multiplicity dependence on the primary energy for a fixed composition $< n_t > = 0.1 < n_{p-Air} > + 0.9 < n_{Fe-Air} >$ in the fusion case and a uniform change in the composition from $< n_t > = 0.25 < n_{p-Air} > + 0.75 < n_{Fe-Air} >$ at 10^{16} eV to $< n_t > = 0.5 < n_{p-Air} > + 0.5 < n_{Fe-Air} >$ at 10^{19} eV in the no fusion case (dashed line).

Table 1

Reaction	$p-Li$	$p-Li$	$p-Li$
p momentum	Experiment	Without fusion	With fusion
	σ for π^+	σ for π^+	σ for π^+
0.200	5.75±0.79	7.06	9.6
0.293	1.89±0.26	0.314	1.79
0.381	0.672±0.046	0.11	0.53
0.474	0.217±0.016	0	0.34
0.580	$(0.509\pm0.044)10^{-1}$	0	0.094
0.681	$(0.128\pm0.012)10^{-1}$	0	0.035
Reaction	$p-Ta$	$p-Ta$	$p-Ta$
p momentum	Experiment	Without fusion	With fusion
	σ for π^+	σ for π^+	σ for π^+
0.200	8.57±1.14	5.65	6.60
0.293	2.20±0.31	0.19	1.57
0.394	0.78±0.068	0.038	0.38
0.489	0.309±0.032	0.032	0.173
0.583	0.135±0.017	0	0.072
0.680	$(0.386\pm0.076)10^{-1}$	0	0.038
	σ for K^+	σ for K^+	σ for K^+
0.539	$(0.241\pm0.100)10^{-1}$	0	0.037
0.584	$(0.372\pm0.763)10^{-2}$	0	0

Table 2

Reaction	$p-Li$	$p-Li$	$p-Li$
p momentum	Experiment	Without fusion	With fusion
	σ for protons	σ for protons	σ for protons
0.385	4.17±0.23	1.24	2.82
0.476	1.76±0.11	0	1.01
0.581	0.61±0.04	0	0.47
Reaction	$p-Ta$	$p-Ta$	$p-Ta$
p momentum	Experiment	Without fusion	With fusion
	σ for protons	σ for protons	σ for protons
0.395	29.9±1.5	15.1	22.3
0.490	13.2±0.7	0	12.57
0.585	5.2±0.3	0	2.5

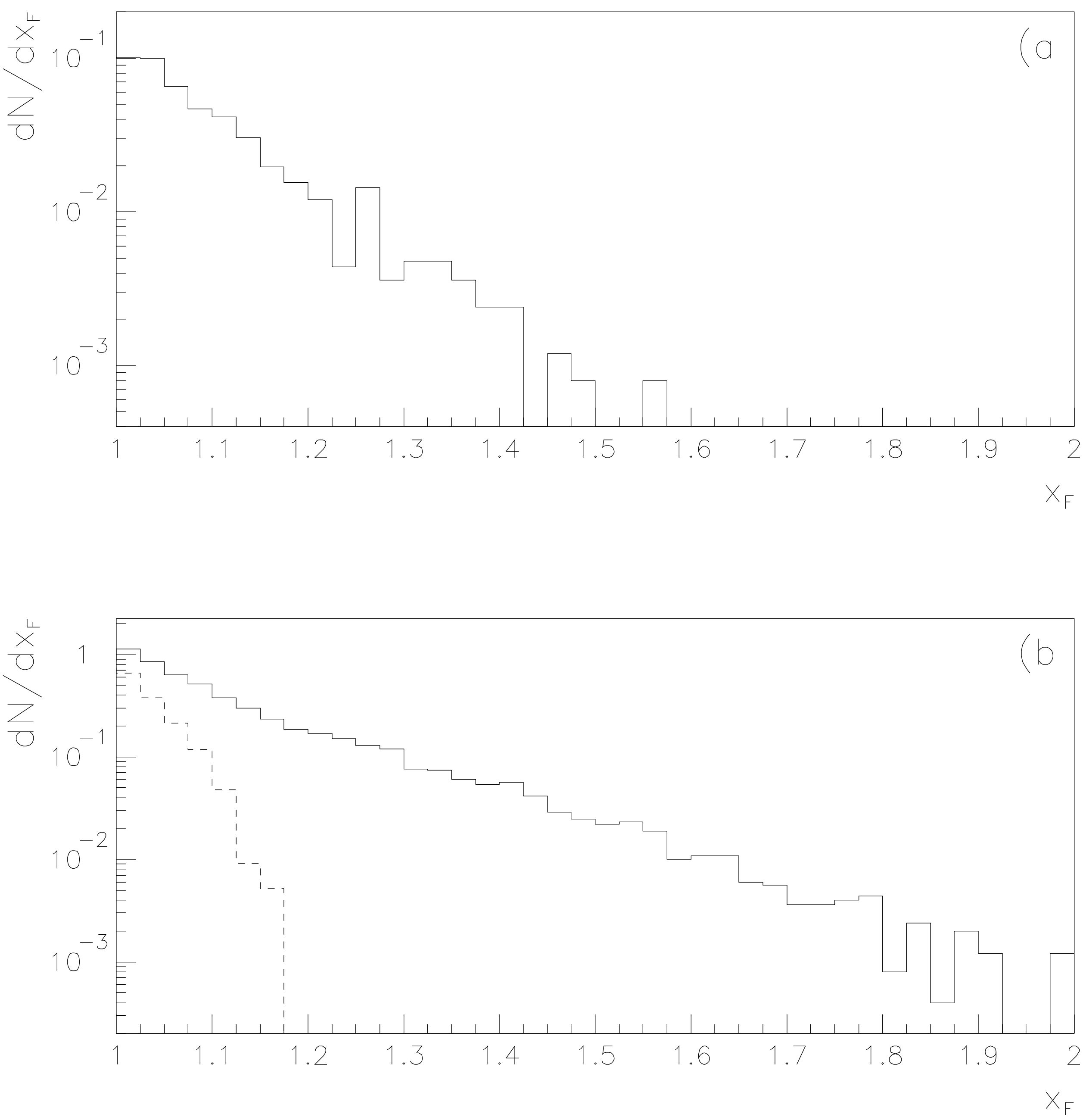
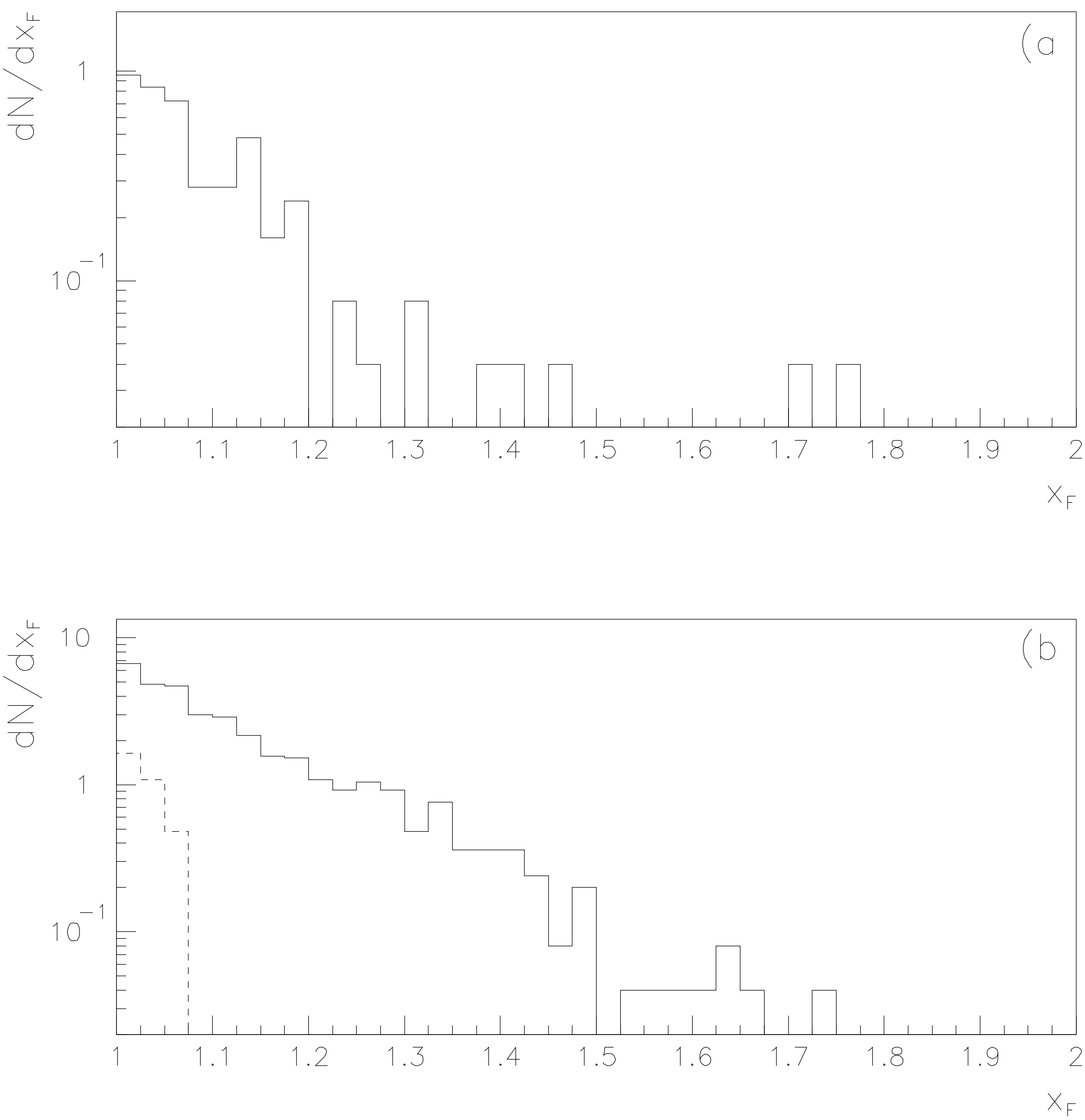

dN/dx_F
(a
10^-1
10^-2
10^-3
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2
x_F
dN/dx_F
(b
1
10^-1
10^-2
10^-3
x_F

Fig. 1


dN/dx_F
(a
1
10^{-1}
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2
x_F
dN/dx_F
(b
10
1
10^{-1}
1
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1.3
1.4
1.5
1.6
1.7
1.8
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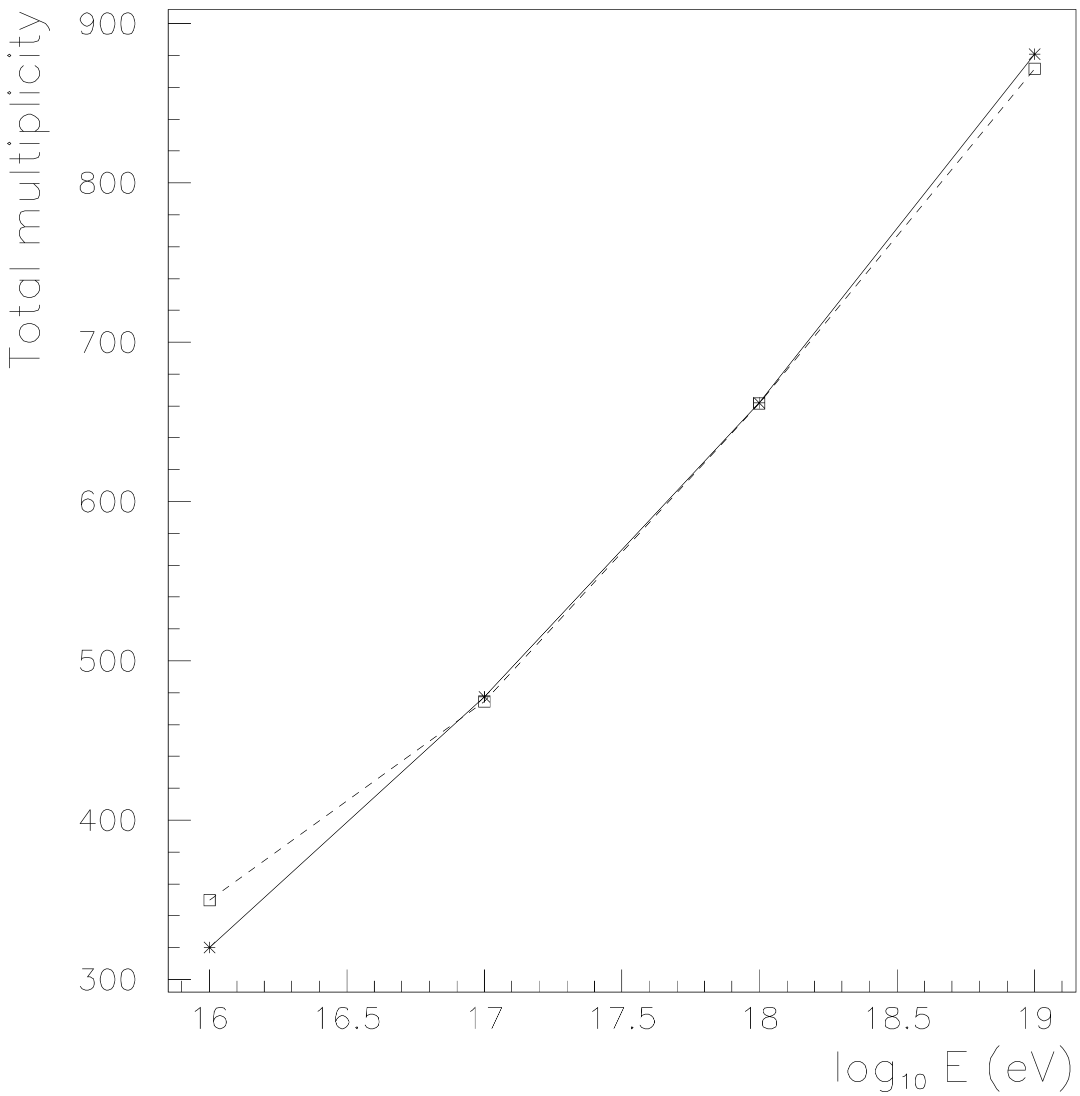
2
x_F

Fig. 2



Total multiplicity
900
800
700
600
500
400
300
16
16.5
17
17.5
18
18.5
19
log$_{10}$ E (eV)

Fig. 3